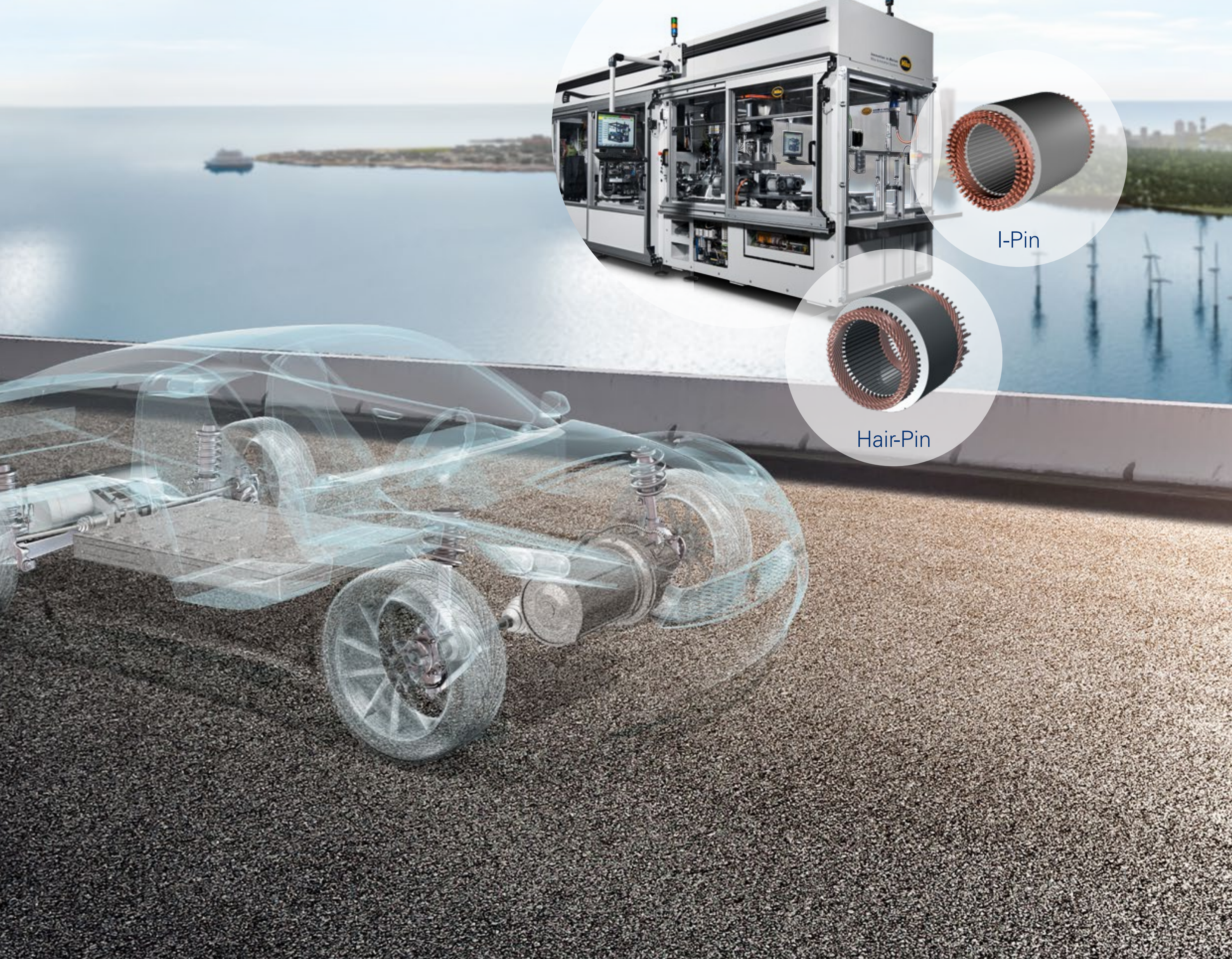
Innovation in Motion

High efficient electric motors with bar windings for serial production

Dr. Andreas Eilenberger
Dipl.-Ing. Roland Hintringer, MBA
Dipl.-Ing. Mateo Primorac
Dipl.-Ing. David Scherrer

all of Miba AG Laakirchen, Austria



39th International Vienna Motor Symposium

ABSTRACT

Electric motors with bar windings are one of the most important innovation directions in the electrification of vehicles. Compared to round wire windings, in most cases bar windings show a higher copper fill factor in the slot and a better thermal connection. The result is advantages in efficiency and power density. First applications of bar windings (hair-pin) were established by American and Japanese OEMs. Other advantages can arise when straight bars (i-pin) are used. The thermal and electrical efficiency in particular can be improved. The thermal efficiency is optimized by using a highly flexible winding head cooling for efficient head dissipation behavior. The electrical efficiency is optimized by using parallel pins to lower existing AC resistance effects at higher frequencies. Additionally, more flexible variations of performance and torque classes are possible by using uneven pins. Furthermore, cost and quality benefits are present when applying the simpler production process of i-pins. The undesirable and complex process steps of the hair-pin forming, the insertion into the lamination core and the cutting are not necessary. This influences the product cost for high-volume serial production. Because of the aforementioned advantages, we are sure that the next generation of high efficient electric motors capable for high volume serial production will use i-pin technology.

INTRODUCTION

The automotive industry is undergoing a transformation: digitalization and electrification are the two main future drivers of change. In the field of electrification, the expectation of innovation is high for automotive OEMs and Tier1s because of the simpler design of electric drivetrains compared to conventional drivetrains.

In the past it was common to use electric motors with round wire windings. The current trend is to use preformed bar windings as seen in various vehicles, especially those manufactured by GM and Toyota. These preformed bar windings are one of the most important innovative steps in hybrid and traction motors today: they are preformed, rectangular shaped copper bars (known as hair-pin) with a higher copper fill factor, a better thermal behavior and thus offering an improved level of efficiency and performance. Furthermore, automated production is possible. The use of rectangular copper bars (known as i-pin) allows fully automated high volume serial production (> 200,000 units per year). This fully automated process offers significant advantages in terms of reducing costs.

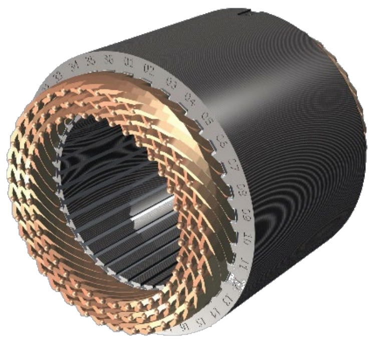


Figure 1: Stator of an electric motor with bar windings with i-pin technology.

Today's bar windings usually have between 2 and 8 pins per slot. By twisting the pins and welding them together the connection is realized in the winding head on the connection side of the stator. Where i-pins are used, the twisting and welding operations are also necessary on the opposite side of the connection.

Figure 2: Schematic of a slot with 2 pins (left) and a larger number of pins (right).

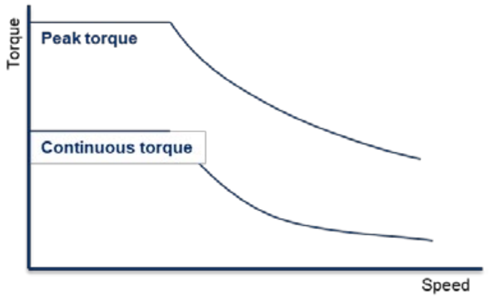
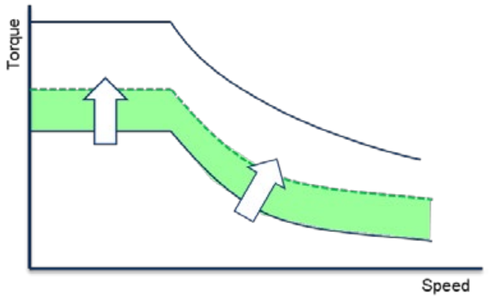
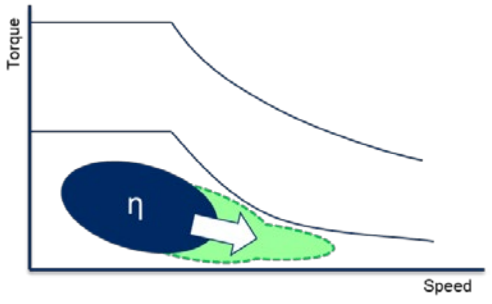
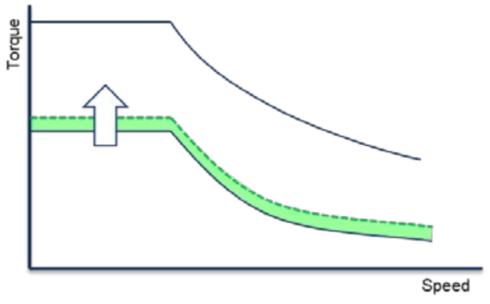
In this paper Miba presents four optimization potentials for bar windings using the i-pin technology. These potentials improve the thermal and electrical efficiency of motors, and allow the bar windings to be used for high volume serial production. The improvements will be used in the next generation of traction motors with bar windings.

No.	Potential Topic	Effect / Description
1	Winding head cooling	Thermal efficiency (**continuous power**) through better mechanical connection on the opposite side
2	Parallel pins	Electrical efficiency (**efficiency**) through lower AC resistance
3	Uneven pins	Easier realization of power and torque classification (**flexibility**)
4	Optimized manufacturing process	Use for serial production (**cost and quality advantage**) / continuous power and prolongation of peak power through lower manufacturing tolerance for i-pins (higher copper fill factor per slot)

Every optimization potential will be quantitatively evaluated for performance (continuous power and duration of peak power), efficiency and cost. It should be noted that this is only an indication as the dependency on geometry and motor topology cannot be assumed in this paper. An evaluation for a specific motor type must be undertaken separately.

OPTIMIZATION POTENTIALS FOR HIGH EFFICIENT ELECTRIC MOTORS

The optimization potential will be visualized on a torque-speed diagram for a permanent magnet synchronous machine (PMSM). Similar results are expected for different topologies of radial flux machines.

Impact on torque-speed diagram	Description
	PMSM torque-speed diagram as basis
	Optimization potential – winding head cooling ▪ Increasing **continuous power** through effective cooling of winding on both winding heads ▪ Prolongation of thermal limited lifetime of electric motor
	Optimization potential – pin parallelization ▪ Enhanced **efficiency** at high speed through reduction of AC resistance (skin effect) in pins ▪ Reduction of battery size or increase in achievable driving range
	Optimization potential – optimized manufacturing process ▪ **Cost and quality advantage** by avoiding hair-pin production and insertion into lamination core ▪ Continuous power: increasing power through lower tolerances (higher copper fill factor, improved thermal connection) ▪ Peak power: advantage when using optimized inverters

Winding head cooling

While the peak power of electric motors is limited by magnetic factors (magnetic saturation of the steel lamination core and stability of the magnets at elevated temperatures), continuous power is mainly influenced by thermal factors.
Several cooling concepts are currently under investigation. These concepts can be divided into two basic types: in the first, there is passive interference as a result of improved material properties and optimized design (thermal conduction); in the second, active interference of a cooling fluid with the winding head, the lamination core or the stator slots (convection) plays a crucial role.
We see the greatest potential in the cooling of the winding head of the stator. Our approach considers both concepts: a combination of active and passive interference using a highly flexible winding head cooling. The resulting advantages are improved connection of the hot spots to the outer housing cooling (1) and direct heat dissipation to the surrounding fluid (2). The results of effective cooling are either higher continuous torque at the same temperature, or lower (thermal activated) copper losses at the same torque.

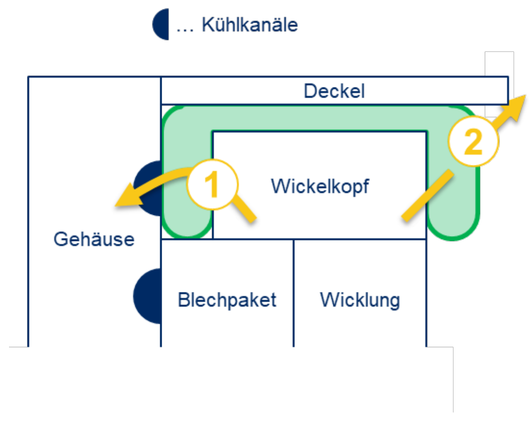


Figure 3: Schematic of a stator with surrounding housing. The electric motor is cooled using highly flexbile winding head cooling (green).

In addition to the flexible cooling, we have used the know-how available in the existing Miba divisions. Together with the Miba Coating Group we are working on direct coating of the lamination cores. The resulting advantages of better thermal connection are especially applicable in smaller hybrid motors. Together with the Miba Power Electronics Group, we are working with established partners on investigating adaptive heat pipes for direct cooling of the stator slots. The advantages of this cooling concept are particularly clear in traction motors.

Performance	↑↑
Efficiency	-
Cost	↓

Parallel pins

Skin and proximity effects, also known as AC resistance, are challenges for conductors with a large cross section at high frequencies: the electromagnetic field of the current in the conductor is responsible for the increased current density at the edges of the conductor. This fact is responsible for increased resistance and losses.

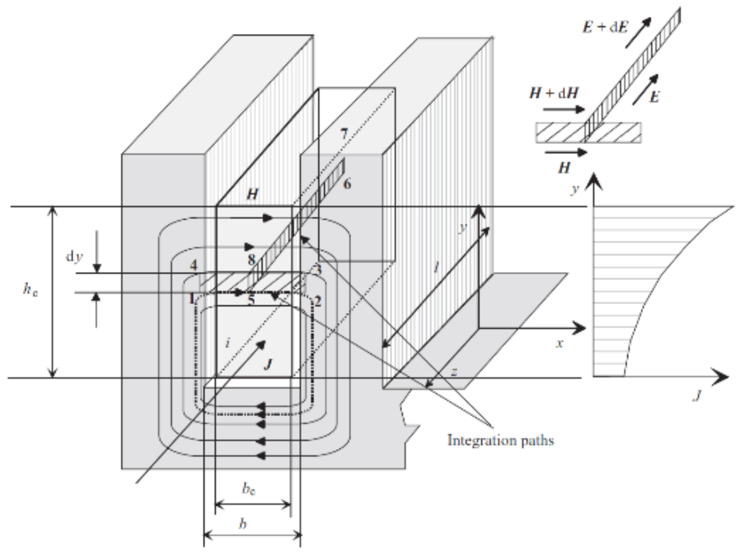
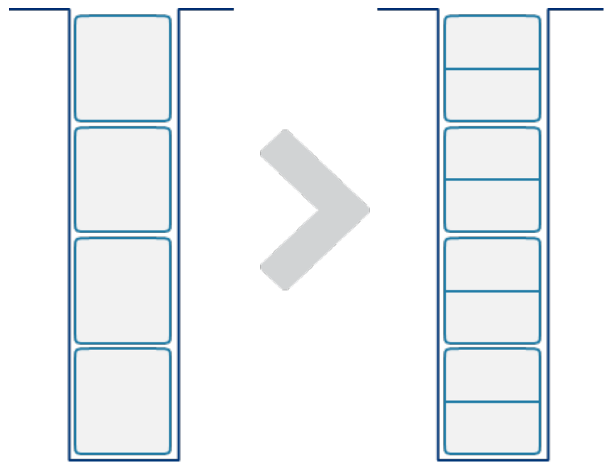


Figure 4: Skin effect in a bar winding. The result is an uneven current density distribution. Source: Design of Rotating Electrical Machines – Juha Pyrhönen (page 257), ISBN 978-0-470-69516-6, John Wiley & Sons.

The skin depth (area of increased current density) is dependent on the conductor material and the frequency level. It describes the displacement and thus the increase in resistance.
The skin depth is proportional to the inverse square root of the frequency. This means that at high frequencies the effective resistance of the conductor increases.
The skin effect is usually relevant at a motor ground frequency of approx. 700 Hz. This frequency is achieved while driving overland or on highways. Here the driving range is a crucial criterion for electric vehicles, making optimization strategies necessary.
One possibility for improving the skin effect is the separation and subsequent electrical insulation of conductors. Each pin is divided in the middle and then reconnected at the pin ends. Usually copper pins are already insulated when processed which results in a double insulation layer in the middle plane between two adjacent pins.



Picture 5: Schematic of parallelization of pins: 4 pins (left) are divided into 8 pins per slot (right).

As the insulation in the middle plane of the pins does not have to undergo a potential difference it can be decreased. The standard process for producing pins is no longer applicable as it would significantly lower the copper fill factor in the slot. In this case the motor performance would decrease.

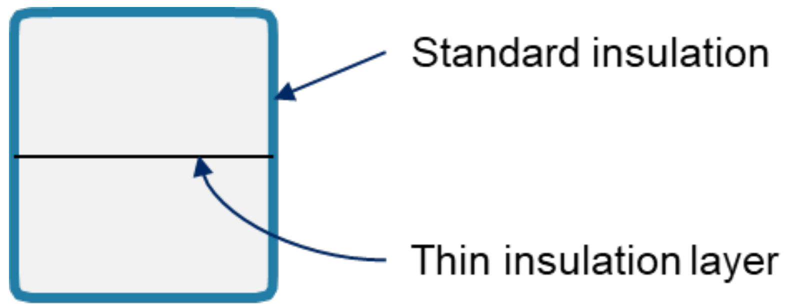


Figure 6: Schematic of parallel pin.

Miba is currently developing a manufacturing process for the parallelization of pins. These pins can then be handled in the assembly process as a single conductor. The process steps of twisting and welding can be undertaken using the standard processes as required, and the AC resistance is significantly decreased.

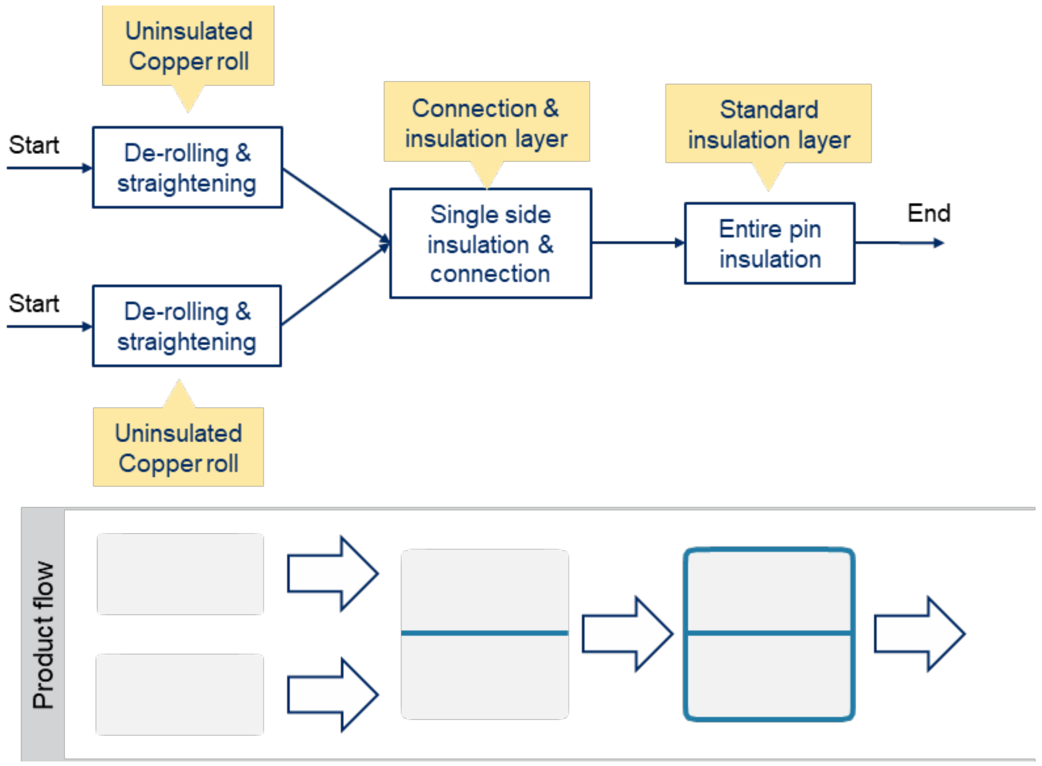


Figure 7: Schematic of a possible manufacturing process for parallelized pins.

The challenge with parallelized pins is the processing of the pin endings, especially when it comes to the welding operation: the weld must not contain any inclusions or insulation material. Therefore a key success factor lies in connecting the pins without a negative impact on weldability.

In summary, the parallelization of pins has a significant impact on AC resistance and thus on the driving range of vehicles, especially when driving overland or on highways.

With current battery prices in the range of EUR 10,000, an efficiency increase of 1% results in a price reduction of EUR 100. This saving is far greater than the higher cost of producing the special pins. Thus it is possible to achieve cost savings for the same driving range, or to increase the driving range without altering the space required to install the battery.

Performance	-
Efficiency	↑↑
Cost	-

Uneven pins

In electric motors it is common to scale performance and torque classes over the active length or the outer diameter of the stator. These variations are usually only possible with adaptions to the tooling or single process steps. Only small changes in the requirements (e.g. a slightly increased torque for derivatives) can be made with existing lamination cores and current/voltage levels.

By using uneven numbers of pins per slot (i.e. using an additional row in the radial direction of the slot) an increase (almost doubling) of winding variations is possible. Different requirements for derivatives of vehicle models are thus possible. A simple calculation should illustrate the advantage of using uneven pins.

Example: Electric motor with M_{max} = 600 Nm @ 600 Arms with a = 8 parallel winding branches Target: slight variation of requirements in torque	
Adjustment with hair-pin → torque by using 6 pins per slot	Adjustment with i-pin → torque by using 7 pins per slot
$M_{max,new} = \frac{M_{max}}{a} * 6 = 450\ Nm$	$M_{max,new} = \frac{M_{max}}{a} * 7 = 525\ Nm$
$\Delta = 25{,}0\%$	$\Delta = 12{,}5\%$

Creating an additional row by using i-pins in a slot does not require much effort. When using an uneven number of pins a connection is also necessary on the opposite side of the stator, not just on the connection side.

This concept avoids the need for adaption or new dimensioning (lamination core, current/voltage levels), and thus no additional costs arise. The flexibility for derivatives in serial production is given.

Performance	-
Efficiency	- (advantage of flexibility)
Cost	↑

Optimized manufacturing process

The hair-pin technology has two advantages over the i-pin technology. Firstly, a lower winding head on the opposite side (also known as hair-pin side), and secondly, having preformed bars avoids the need for several process steps. The doubling of the number of welding points and the need to isolate them is often considered critical for i-pin technology.

Nevertheless, there are not only advantages but also significant disadvantages. Three process steps have a negative influence on the manufacturing tolerance: the forming of straight conducting bars to preformed bars (hair-pins), the complex insertion of the hair-pins into the lamination core (especially for short pitch windings) and the cutting of the sharpened hair-pins (while creating unwanted chips) in preparation for welding the pins. The outcome is a negative influence on manufacturing tolerances which is especially notable when smaller dimensions of copper bars are used.

The three process steps noted above are not necessary when using i-pins. The consequence is that machine cost (and therefore also product cost) are reduced. This reduction is dependent on the lot size and the geometrical dimensions but is in the range of 5–10% of the product cost. Additionally, a higher manufacturing tolerance is achievable, positively influencing performance by allowing a higher copper fill factor and better thermal behavior.

For i-pins the surrounding tolerance is generally below 0.1 mm (note: this is a realized project, different copper dimensions must be investigated separately). Compared to hair-pins with a surrounding tolerance of approximately 0.2 mm, this has a tremendous effect on the copper fill factor, resulting in an increase of between 8–15%. (calculation: 8 pins per slot, standard stator slot, insulation material and copper dimensions). With an increased number of pins per slot, higher percentage rises in the copper fill factor are achievable.

It should be noted here that the additional copper fill factor, the result of lower manufacturing tolerance, is achieved without additional cost. Furthermore, the cost-intensive and cycle-time-reducing process steps of the hair-pin (as mentioned above) are unnecessary. As a result, the investment costs for machines, and thus the product costs, are minimized.

Performance	↑↑
Efficiency	-
Cost	↑

Summary

One of the most promising innovation directions for automotive electric motors lies in using bar windings for stators. These windings generally exhibit a higher copper fill factor in the slot and a better thermal connection compared to conventional round wire windings. Another advantage is their suitability for fully automated production, allowing their use in high volume serial production. In this paper, we have demonstrated four optimization potentials for i-pin technology:

1. Winding head cooling
2. Parallel pins
3. Uneven pins
4. Optimized manufacturing process

The four optimization potentials for i-pin technology shown here offer a significant advantage over hair-pins, especially potential 2, 3 and 4. It has been demonstrated how performance and efficiency can be increased, and costs reduced. Potential 1 is also applicable for hair-pin technology, although the effect is greater with i-pins due to the open winding heads on both sides of the stator.

Due to the cost and quality advantages with high volume serial production, and the benefits gained by using parallelized pins as shown above, plus the flexibility of winding configurations through the use of uneven pins and the improved manufacturing tolerance, we are confident that the next generation of high efficient electric motors for high volume serial production will use i-pin technology.

MIBA 2020

DYNAMIC EVOLUTION

As a technology leader and global company, we are making an active contribution to technical progress and global economic growth. Global population growth, climate change and the scarcity of resources demand innovative solutions. We are preparing for these tasks and have defined our focus for the next few years. Change always means new possibilities and opportunities to be exploited. With Miba 2020, we are heading into the future with confidence, a clear vision, strategy and ambitious targets.

OUR MISSION

Innovation in Motion –
Technologies for a Cleaner Planet

OUR VISION

No power train without Miba technology

OUR GOALS

- Profitable growth to over EUR 1 billion
- Increase in revenue from core business and through M&A
- Global number 1 in our market segments

OUR STRATEGY

Strive for technology leadership in demanding, financially attractive market segments.
"Dynamic Evolution" as the overarching guiding concept supported by three main pillars: Global Growth, Innovation and Technology, People

OUR VALUES

- Technology Leadership
- Lifelong Learning
- Entrepreneurship
- Passion for Success

www.miba.com

Contact
Miba AG
Dr.-Mitterbauer-Str. 3
4663 Laakirchen, Austria
T +43 7613 2541 0
info@miba.com